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Impacts of climate variability and change on seasonal drought characteristics of Pakistan

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ABSTRACT

Assessment of the influence of climate variables on drought characteristics is important for adaption to changing pattern of droughts due to climate change. The objective of this study is to assess the changing characteristics of droughts due to climate variability and change during two major cropping seasons (Rabi and Kharif) for the period 1901–2010 over the diverse climate of Pakistan. The gauge-based gridded precipitation and temperature data with a spatial resolution of 0.5° is used for the reconstruction of droughts using standardized precipitation evapotranspiration index (SPEI). The temporal variations in droughts and their relationships with precipitation and temperature are assessed using a 50-year moving window with a 10-year time step. The annual maximum series (AMS) approach is used to estimate the return periods of seasonal droughts and the modified Mann-Kendal trend test is applied to assess the significance of trends in climate variables and drought index. The results showed that drought severity is increasing in the predominantly arid and semi-arid regions for both cropping seasons, while it is decreasing in western disturbance (WD) influenced high winter precipitation region during Rabi season. Temperature is found as the dominating factor for defining droughts in arid and semi-arid regions while the precipitation in WD influenced region. An increase in temperature in the range of 0.001 to 0.025 °C per year and almost no change in precipitation have caused decreases in Rabi SPEI in the range of −0.011 to −0.025 per year in the arid region. On the other hand, increases in precipitation in the range of 1.01–2.0 mm/year have caused increases in Kharif SPEI in WD influenced region in the range of 0.016–0.02 per year. However, rises in temperature in most part of the country has caused an increase in drought frequency in both seasons in the areas where droughts are less frequent. The results indicate that rising temperature due to global warming would increase drought severity and frequency in most part of the predominantly arid country.

1. Introduction

Increased frequency and severity of droughts caused by rising temperature and changing precipitation have been reported in many parts of the world (Duffy et al., 2015; Gocic and Trajkovic, 2014; Hui-Mean et al., 2018; Zhao and Dai, 2015). Droughts are directly related to water availability and therefore, changes in drought characteristics as a result of climate change will define water stress and food security in the context of global warming (Nam et al., 2015; Touma et al., 2015). Understanding the influence of climate variables on droughts in different climatic regions is very important for climate change adaptation and mitigation for a sustainable development. Though droughts have long-lasting impacts on natural and human systems in any climatic region, higher temperature, evapotranspiration and erratic precipitation have made the arid and semi-arid regions physically highly vulnerable to droughts (Adnan et al., 2017a). Therefore, changes in droughts due to climate change can have far-reaching impacts in arid and semi-arid regions where economies are mainly dependent on crop agriculture (Miyan, 2015).

Pakistan, located in a predominantly arid region is characterized by low precipitation and high temperatures. The economy of the country is highly dependent on crop agriculture (Kazmi et al., 2015). The agriculture sector also plays a vigorous role in the economic development of the country. The sector contributes 24% to gross domestic product (GDP) and employs about 43% of the total labor force. A large number of Pakistan's population lives in rural areas and relies on crop agriculture as their source of income. The heavy reliance of economy on agriculture has made Pakistan highly vulnerable to climate change induced droughts.

A number of studies have been conducted for characterization of

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droughts in Pakistan at regional and national scales such as (Adnan et al., 2017b; Ahmed et al., 2015; Haroon et al., 2016; Xie et al., 2013). Various indices, including standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), Palmer Z-index, drought severity index, standardized precipitation temperature index have been used in the previous studies to assess droughts for various time scales ranging from 3 months to 4 years. Both observed and gridded climate data have been used to show the spatio-temporal patterns of the droughts. However, none of the studies attempted to assess the impacts of climate variability and changes on the characteristics of droughts in Pakistan.

Pakistan is one of the most vulnerable countries to climate change. The temperature of the country is rising and precipitation patterns are changing. Recent studies reported that the mean surface temperature in Pakistan has increased by 0.1 °C/decade over the period 1960–2010 (GOP, 2013; IPCC, 2007; Khan et al., 2018; Syed et al., 2013) and the precipitation has become unreliable and unpredictable (IPCC, 2007; Syed et al., 2014). An increase in precipitation during monsoon, particularly in some monsoon dominated regions and decrease in precipitation during winter in the arid region has also been reported (Ahmed et al., 2017b; GOP, 2013). It is anticipated that the changes in climate have changed the characteristics of droughts in Pakistan. However, owing to high diversity of climate and various patterns of the changes in climate in different regions and seasons, the impact of climate change would have a different impact on droughts in different parts of the country. Furthermore, the influence of climate on droughts can also vary with time. Besides, it is important to assess the climate change impacts on droughts during cropping season as the droughts are found to be more destructive when they occur during cropping seasons.

Thus, the major objective of the study is to analyze the changing characteristics of droughts during major crop growing seasons (Rabi and Kharif) in order to assess the impact of climate variability and changes on the characteristics of seasonal droughts over the diverse climate of Pakistan. Several drought indices have been developed and applied for the characterization of droughts. Among them, the SPI is of the most widely used drought indicator. However, it only considers precipitation to characterize droughts. Evapotranspiration is another major factor that defines the severity and intensity of droughts, particularly in arid and semi-arid regions. Therefore, standardized precipitation evapotranspiration index (SPEI), which combines the effect of precipitation and temperature to quantify the condition of droughts is used. The gauge-based gridded precipitation and temperature data provided by the Global Precipitation Climatology Centre (GPCC) of the Deutscher Wetterdienst (Becker et al., 2013) and Climatic Research Unit (CRU) of the East Anglia University (Harris et al., 2014) are used for the assessment of the changes in drought characteristics over the period 1901–2010 using a 50-year moving window with 10-year time step. A modified version of Mann-Kendall trend (MMK) test which can distinguish natural variability of climate from anthropogenic climate change is used for the analysis of secular trends in climate variables and drought index. The impact of climate change is supposed to be different for different climatic regions. It is expected that the assessment of the changes in seasonal drought characteristics over a diverse climate of Pakistan would help to understand how future climate variations may affect droughts in different types of climates and cropping seasons.

2. Study Area and Datasets

2.1. Study area

Pakistan (Lat: 23°–37°N; Long: 61°–78°E), located in south Asia (Fig. 1) borders with China in the north, the Arabian Sea in the south, India in the east, Iran and Afghanistan in the west. The topography and climate of the country has lots of variations. The annual average of mean temperature varies from near 0 °C in the extreme north to 32 °C in the southern coastal region. Pakistan is largely an agriculture-based country. The crops in the country are grown and harvested in two distinct cropping seasons namely Kharif (summer) and Rabi (winter) (Sheikh et al., 2009). Kharif season begins in May when the soil moisture content from precipitation is sufficient to support rain-fed crops and ends in October. The major Kharif crops include cotton, sugarcane, rice, and maize. The exact timing of the Rabi season varies by latitude and is influenced by the departure date of monsoon. However, on average, the Rabi season begins in November and ends in April. The Rabi crops are region-specific which include wheat, barley, peas, gram and mustard (Ahmed et al., 2015).

2.1.1. Climate during cropping seasons

The spatial distribution of precipitation during Rabi and Kharif for the period 1901–2010 are shown in Fig. 2a– respectively. Precipitation is equally divided into ten classes between 9 mm and 900 mm. The figure shows a large variation in precipitation in both seasons. The precipitation gradually decreases from the north towards the south and relatively higher at northern areas and lower at southern parts. Since the country is mostly characterized by arid and semi-arid climate; the majority of regions have < 190 mm precipitation during Kharif and < 100 mm during Rabi season. A very small area receives precipitation > 700 mm. Highest precipitation is recorded in northern areas near the foothills of Himalaya in both cropping seasons.

The precipitation during Kharif season mainly occurs due to the influence of monsoon. The monsoon of Pakistan flows in two branches, the Southeastern monsoon (SEM) which brings rainfall from the Arabian Sea, is considerably very low and the Northeastern monsoon (NEM) which is the deflected monsoon currents travelling from the Bay of Bengal along the foothills of the Himalayas and enter the northeastern part of the country (Imran et al., 2014). Therefore, the precipitation is higher in NEM dominated northern areas while lower in SEM dominated southeast region. The SEM enters through the southeastern part of the country and passes through the land from southeast to northwest. As the monsoon continues, the air moisture content reduces and the monsoon precipitation gradually decreases from east to west. Therefore, most of the eastern part of the country annually receives < 100 mm precipitation are categorized as arid land while the central and southern parts of the country which receive an annual precipitation in the range of 100–400 mm are considered as semi-arid land.

The precipitation during Rabi season occurs due to western disturbances (WD) originated in the Mediterranean Sea or Atlantic Ocean. These winds lose air moisture during long travel over the land and therefore, bring only a small amount of rain in various parts of Pakistan (Ahmed et al., 2017b). Conversely, western highlands, particularly the lands in the foothill of sub-Himalayan region receive more precipitation during winter (Sheikh et al., 2009).

The spatial distributions of mean annual temperature for Rabi and Kharif seasons are shown in Fig. 3a-b respectively. Temperature is equally divided into 24 classes ranging from < −12 °C to > 34 °C. The Rabi season is found to be relatively cold (-14 °C to 24 °C), as it coincides with the winter season, while the average Kharif temperature in Pakistan varies from 1 °C to 34 °C. The lowest temperatures in both seasons are observed in elevated northern areas of Pakistan.

2.2. Datasets

One of the major problems in hydro-climatological investigations in most parts of the world is the lack of availability of long records and reliable climatic observations (Ahmed et al., 2018). To overcome these difficulties, numbers of multi-source climate data products such as in-situ, satellite-based, reanalysis and their combination have been developed. Among those the in-situ based gridded data are often used because of their spatial and temporal continuity and availability over longer periods (Kishore et al., 2015). In the present study, the gridded monthly precipitation data of GPCC and the monthly average of daily

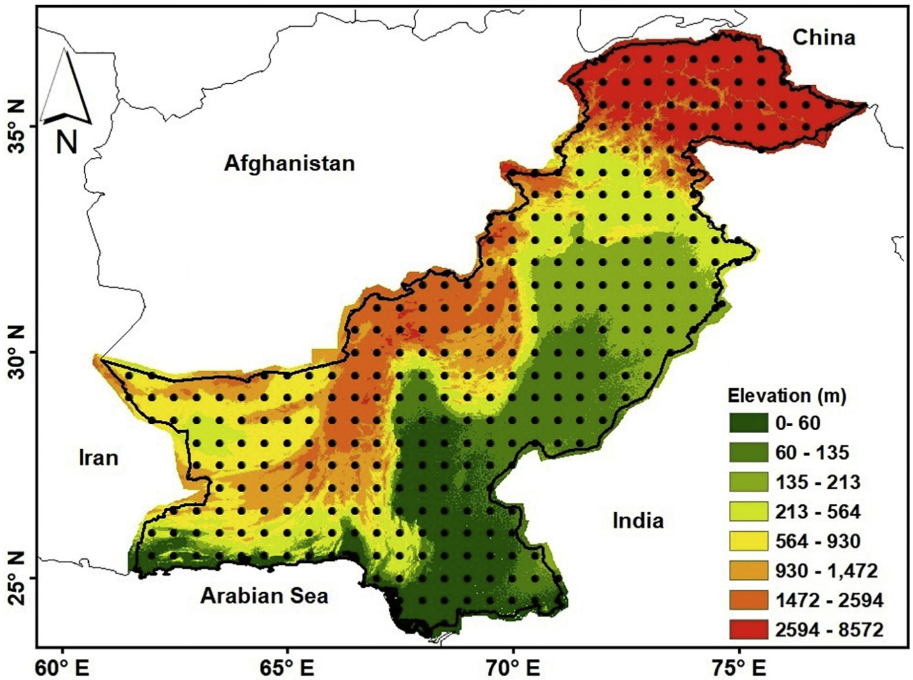

Fig. 1. The geographical location and the topography of Pakistan. The black dots in the map represent the GPCC and CRU grid points.

temperature data of CRU with a spatial resolution of 0.5° (347 grid points covering Pakistan) for the period 1901–2010 is used. Both datasets were selected based on their availability over longer periods (i.e. > 100 years).

The main advantages of using GPCC data are: (1) the quality of the dataset is good enough for hydro-climatic analysis; (2) it is a climate model derived dataset, which uses the highest number of observed precipitation records; (3) time span of data is long enough for conducting hydro-climatic studies (Spinoni et al., 2014). Studies reported better performance of GPCC compared with other gridded precipitation datasets using conventional statistical methods (Ahmed et al., 2017a; El Kenawy and McCabe, 2015; Kishore et al., 2015). In addition to this, GPCC data has been found to have good correlation with observed data of Pakistan (Adnan and Ullah, 2015; Ahmed et al., 2017a; Ahmed et al., 2015). On the other hand, the CRU database is developed from gauge measurements obtained from about 4000 weather stations located around the world. All the collected data are passed through two-stage extensive manual and semi-automatic quality control measures to develop the gridded monthly temperature (Harris et al., 2014). CRU temperature data was also found to perform better compared with other gridded temperature data in Pakistan (Afzaal et al., 2009; Asmat et al., 2017).

3. Methodology

3.1. Standardized precipitation evapotranspiration index

The Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2010) considers potential evapotranspiration (PET) in addition to precipitation in assessing drought and therefore found to be more effective to detect the temporal variability of droughts in the context of climate change (Frank et al., 2017; Mohsenipour et al., 2018; Song et al., 2015). In SPEI, the accumulated difference between monthly precipitation and potential evapotranspiration at different time scales are fitted with a three-parameter probability distribution function (PDF). The estimated parameters of the best fitted PDF are used to calculate the SPEI. An SPEI value between −1.0 and − 1.5 indicates moderate drought, between −1.5 and − 2.0 indicates severe drought and below −2.0 represents extreme drought.

Different temperature, radiation and mass transfer-based methods are available for the estimation to PET (Tukimat et al., 2012). Stagge et al. (2014) suggested that SPEI is not sensitive to the method used for the estimation of PET. On the other hand, Beguería et al. (2014) reported that the use of different PET methods produced significant differences in the series of the calculated SPEI in some climatic regions. They proposed the use of the Penman-Monteith method as the first choice, followed by Hargreaves and Thornthwaite methods for the calculation of SPEI. The Thornthwaite method requires only average temperature for the calculation of PET and therefore, most widely used in the regions where data availability is limited (Shiru et al., 2018). Therefore, Thornthwaite method is used for the estimation of PET.

3.2. Estimation of return period of seasonal droughts

The drought for a season is determined by computing the SPEI for a time-scale equal to the time span of the season in the last month of the corresponding season. Therefore, 6-month SPEI computed in the month of October and April are used for the analysis of Kharif and Rabi droughts respectively. Annual maximum series (AMS) of SPEI is used to estimate the return period of seasonal SPEI values using frequency analysis. The AMS is based on the single drought event at each year, provided that it exceeds a given threshold. In the present study, SPEI value less than −0.5 is considered as drought and therefore, the years without droughts are assigned a value of zero. The drought frequency analysis is carried out only on the non-zero values and a correction is conducted using non-exceedance probability (F′) in order to account for the zero values,

$$F' = q + (1 - q)F \tag{1}$$

where F is the non-exceedance probability value obtained using frequency analysis on the non-zero values, and q is the probability of zero values, which can be calculated as the ratio of the number of time intervals without drought occurrences to the total number of time intervals in the recording period (Ahmed et al., 2015; Alamgir et al., 2015; Mohsenipour et al., 2018; Santos et al., 2011).

In this study, the SPEI values of Rabi and Kharif seasons are fitted

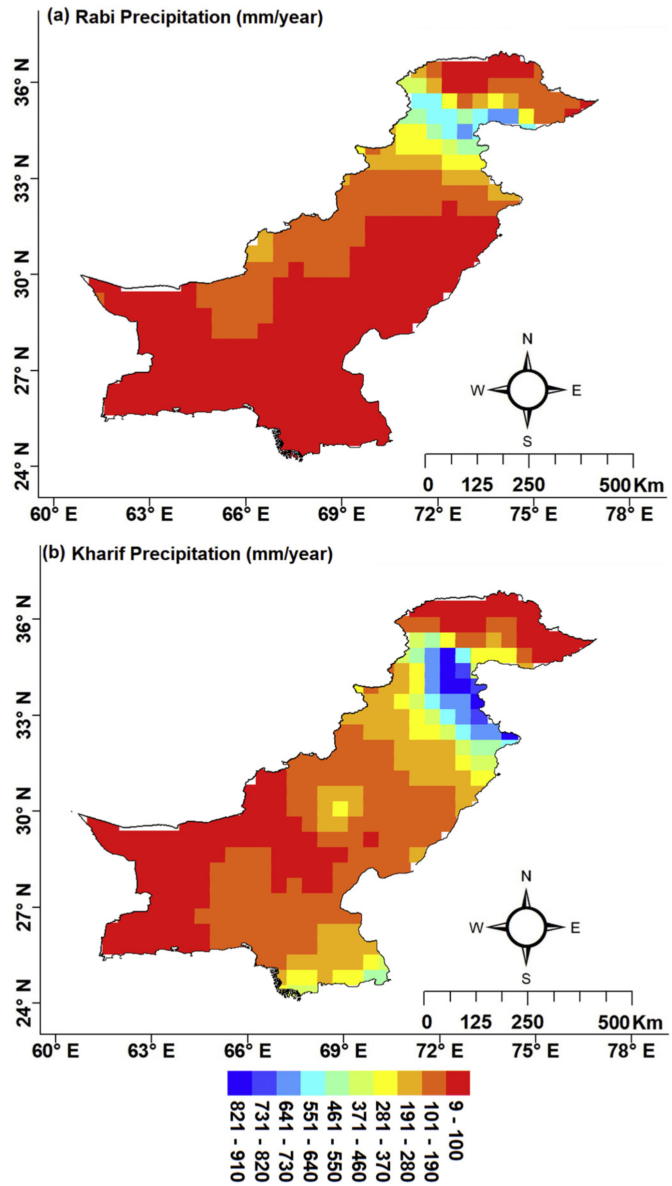

Fig. 2. Spatial distribution of (a) Rabi; and (b) Kharif precipitation over Pakistan.

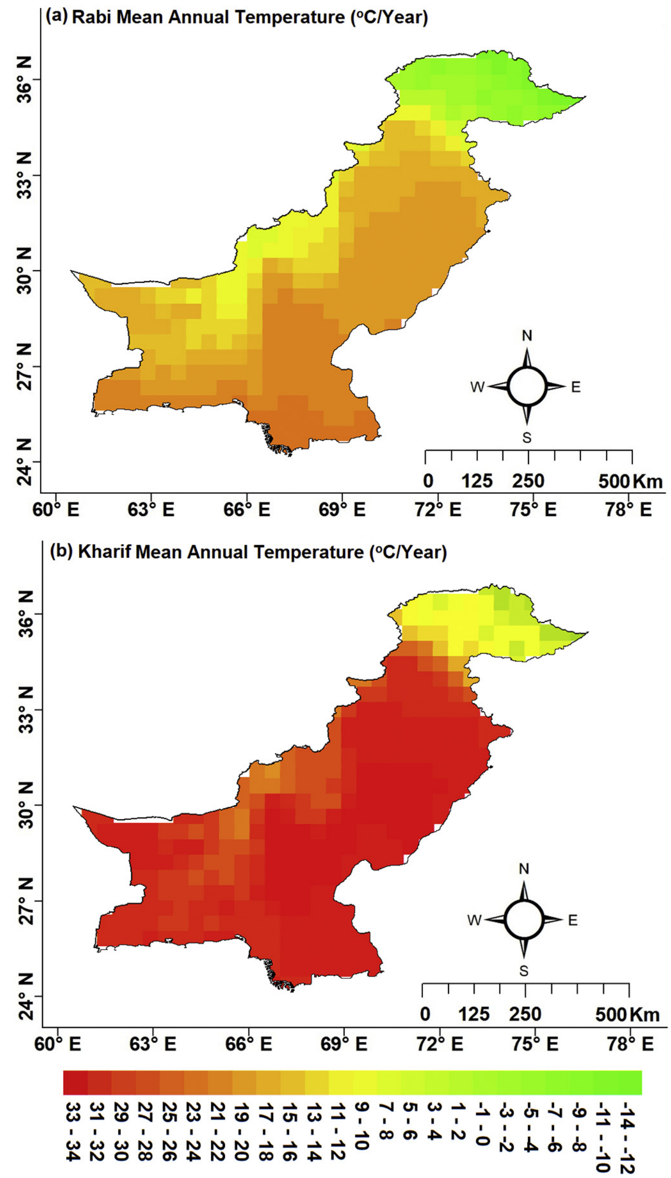

Fig. 3. Spatial distribution of (a) Rabi; and (b) Kharif mean annual temperature over Pakistan.

with Normal, Lognormal, Weibull, Gamma and Extreme Value-I distributions. Kolmogorov-Smirnov (KS) test is conducted to estimate the goodness of fit to a particular distribution. The KS test statistics showed that the null hypothesis of sample distribution similar to Lognormal distribution cannot be rejected for any seasonal SPEI series. Therefore, Lognormal distribution is used for the estimation of distribution parameters of seasonal droughts.

3.3. Sen's slope estimator

The Sen's slope estimator (Sen, 1968) is used to estimate the rate of change in SPEI, precipitation and temperature. In Sen's slope method, the change in a time series (Q_{med}) is computed as the median of N slopes estimated from consecutive two points of the series,

$$Q = \begin{cases} Q([(N+1)/2]) & \textit{if n is odd} \\ \dfrac{Q_{[N/2]} + Q_{[(N+2)/2]}}{2} & \textit{if n is even} \end{cases} \tag{2}$$

3.4. Modified Mann-Kendall test

The modified Mann-Kendall (MMK) test is used to assess the significance of trend in SPEI, precipitation and temperature. The classical Mann-Kendall test statistic (S) for a time series, x with n number of data points is calculated as (Mann, 1945),

$$S = \sum\nolimits_{k=1}^{n-1} \cdot \sum\nolimits_{i=k+1}^{n} \text{sign}\,(x_i - x_k) \tag{3}$$

where

$$sign\,(x_i - x_k) = \begin{cases} +1 & \text{when } (x_i - x_k) > 0 \\ 0 & \text{when } (x_i - x_k) = 0 \\ -1 & \text{when } (x_i - x_k) < 0 \end{cases} \tag{4}$$

The significance of the trend is the calculated using Z statistics as,

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var\,(S)}} & when\ S > 0 \\ 0 & when\ S = 0 \\ \frac{S-1}{\sqrt{Var\,(S)}} & \text{when } S < 0 \end{cases} \tag{5}$$

where, ***Var*** (***S***) is the variance of *S*.

In MMK test (Hamed, 2008), the significant trend estimated using MK test is first removed. The equivalent normal variants of rank (R_i) of the de-trended series is then estimated as,

$$Z_i = \phi^{-1}\left(\frac{R_i}{n+1}\right) \tag{6}$$

where, ϕ^{-1} is the inverse standard normal distribution function. The correlation matrix of self-similarity of the time series or the Hurst coefficient (H) is derived using the following equation (Koutsoyiannis, 2003):

$$C_n(H) = [\rho_{|j-i|}], \quad for\ i = 1{:}\ n;\ j = 1{:}\ n \tag{7}$$

$$\rho_l = \frac{1}{2}\left(|l+1|^{2H} - 2\,|l|^{2H} + |l-1|^{2H}\right) \tag{8}$$

where, ρ_l is the autocorrelation function of lag l for a given H. The value of H is obtained using maximum log likelihood function. The significance level of H is determined by using mean and standard deviation for $H = 0.5$. If H is found significant, the biased estimate of the variance of S is calculated for given H as,

$$V(S)^{H'} = \sum_{i<j} \cdot \sum_{k<l} \frac{2}{\pi} \sin^{-1}\left(\frac{\rho\ |j-i| - \rho\ |i-l| - \rho\ |j-k| + \rho\ |i-k|}{\sqrt{(2-2\rho\ |i-j|)(2-2\rho\ |k-l|)}}\right) \tag{9}$$

The bias in estimation of $V(S)^H$ is removed using a bias correction factor, B as below:

$$V(S)^H = V(S)^{H'} \times B \tag{10}$$

where B is a function of H. The significance of MMK test is computed using eq. (5) by replacing $V(S)$ with $V(S)^H$.

The MMK test can remove the short- and long-term autocorrelation in time series and therefore found more reliable in detection of secular trends in climate (Nashwan et al., 2018; Salman et al., 2017).

3.5. Spatial patterns of trends

Drought is a complex phenomenon that varies over time and space (Patterson et al., 2013). Therefore, a complete understanding of drought requires studying their spatial extents. In the present study, the magnitude of change in SPEI, precipitation and temperature estimated using the Sen's slope estimator at all the GPCC/CRU grid points over Pakistan are presented using color ramps. The change at each grid point is presented in the original resolution of GPCC/CRU data (0.5° × 0.5°). Symbols '+' or '-' are used to show the significance of trend estimated using MMK test at each grid point.

4. Results

4.1. Spatial pattern of the trends in seasonal droughts

The spatial patterns of the trends in SPEI during Rabi season are presented in Fig. 4a. Positive (+) and negative (−) signs in the figure show the significance of decreasing and increasing trend at the 95% confidence level respectively. The figure clearly indicates significant increase in drought severity (increase in negative SPEI) in a major portion of the country during 1901–2010. It is observed that most of the significant increase in Rabi SPEI is in arid and semi-arid southern parts,

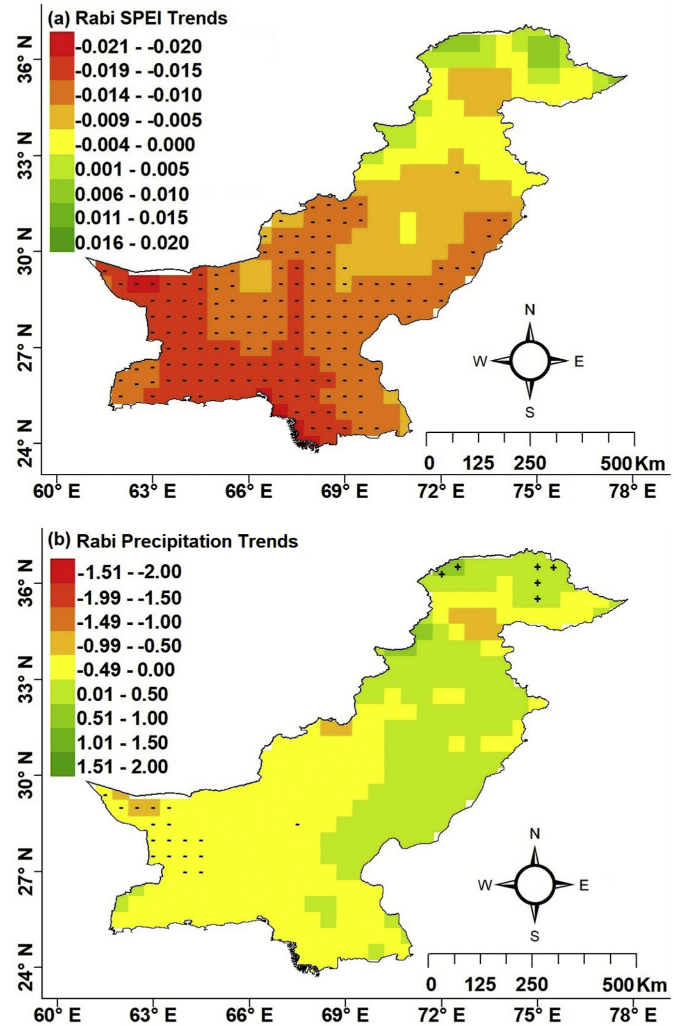

Fig. 4. Spatial patterns of trends in (a) SPEI; and (b) precipitation during Rabi season using MMK test. The plus (+) and minus signs (−) indicate increasing and decreasing trend respectively at the 95% level of confidence.

which are historically more affected by droughts. On the other hand, no significant change in drought severity during Rabi season is observed in WD influenced northern high winter precipitation region. The spatial distributions of the trends in Rabi precipitation are shown in Fig. 4b. The values in the legend of the map represent the changes in precipitation in mm yr^{-1} during the season. The result shows almost no change in precipitation during Rabi season, except a decreasing trend at a few grid points in the southwest arid region and increasing trend at six grid points in the WD influenced high winter precipitation region in the north.

Fig. 5 shows a significant increase in temperature during Rabi season (0.001 to 0.025 °C/year) over almost the whole country. The highest increase (0.011 to 0.025 °C/year) is mostly observed in the southern and southwestern arid region. Almost no change in precipitation, but an increase in temperature has caused a significant decrease in SPEI in the range of −0.009 to −0.021 per year during Rabi season in the arid region of the country. The increasing severity of droughts is found higher in the southwestern arid region where the temperature is increased at a higher rate.

The trends in Kharif SPEI and precipitation are presented in Fig. 6a-b respectively. Both positive and negative trends are observed in Kharif SPEI. Significant increase in drought severity (decrease in SPEI) is found at more grid points compared to decrease in SPEI which indicates an overall increase in Kharif droughts in the study area over the last

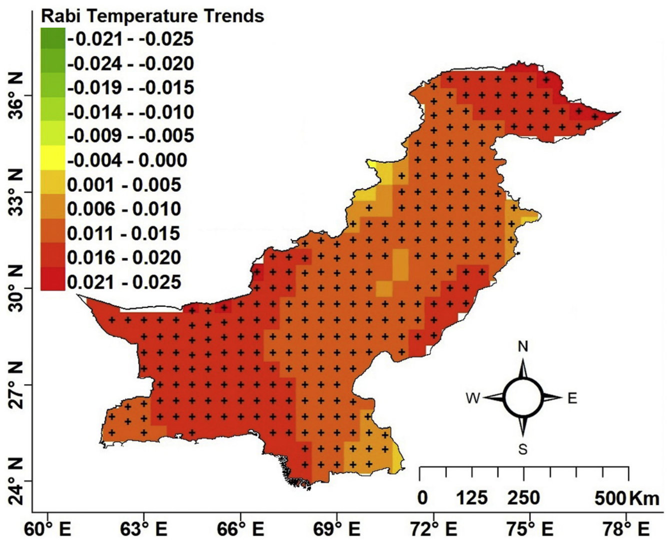

Fig. 5. Spatial patterns of the trends in temperature during Rabi season obtained using MMK test. The plus (+) sign indicates an increasing trend at the 95% level of confidence.

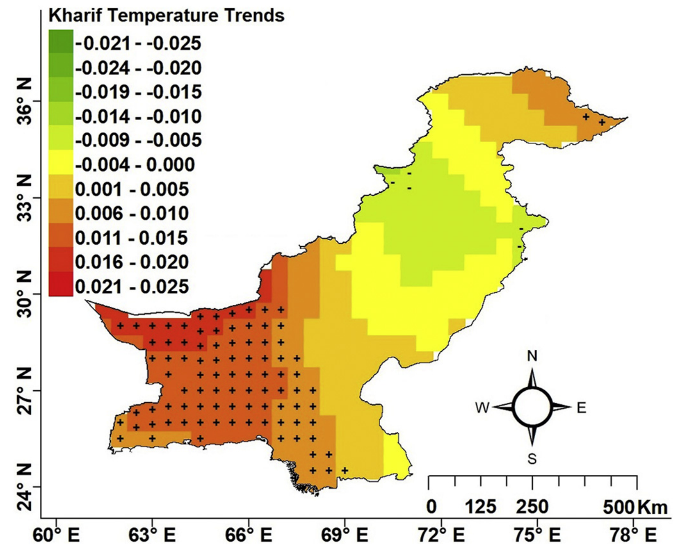

Fig. 7. Spatial patterns of the trends in temperature during Kharif season obtained using MMK test. The plus (+) and minus signs (−) indicate increasing and decreasing trend respectively at the 95% level of confidence.

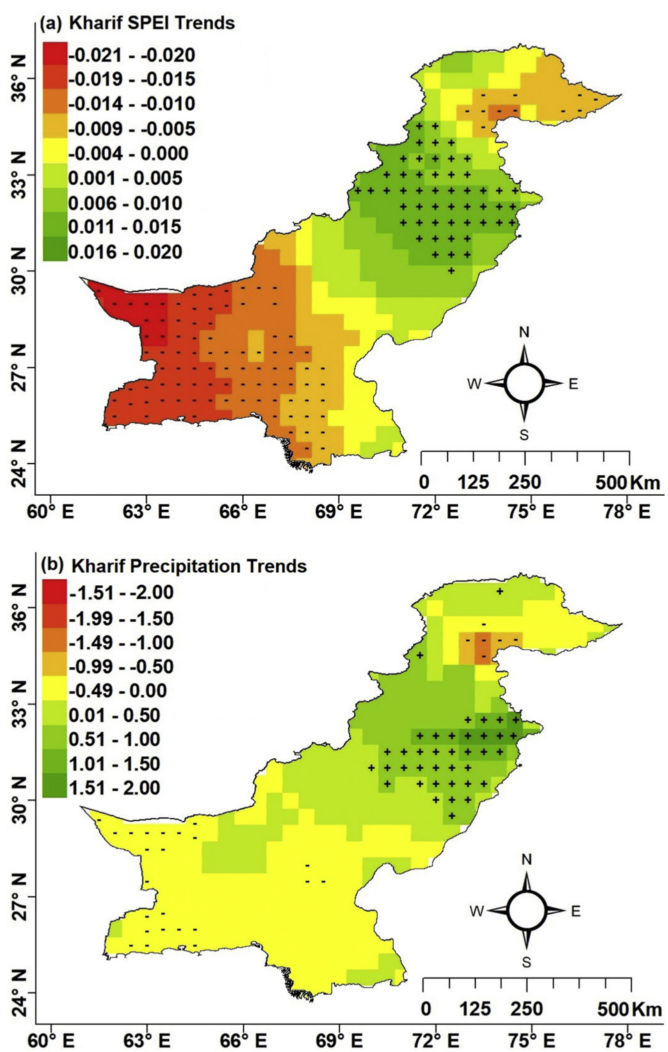

Fig. 6. Spatial patterns of the trends in (a) SPEI; and (b) precipitation during Kharif season obtained using MMK test. The plus (+) and minus signs (−) indicate increasing and decreasing trend respectively at the 95% level of confidence.

century. Most of the increasing trends are found in southern parts of the country. Besides, increasing severity of droughts is also noticed in the northeast corner. On the other hand, an increasing trend in Kharif SPEI (decrease in drought severity) in the range of 0.016 to 0.020 is observed in a small portion where Kharif precipitation is dominated by NEM.

Significant increase in Kharif precipitation (Fig. 6b) is observed over a large area in the NEM dominated northeastern part in the range of 1.01 to 2.0 mm/year, while a decrease at a few grid points in the western corner. On the other hand, temperature is found to increase only in the southwest arid region (Fig. 7). The increase in precipitation and no change in temperature have caused increase in SPEI (decrease in drought severity) during Kharif season over a large area in the NEM dominated region, while a large increase in temperature and a decrease or no change in precipitation has caused an increase in drought severity in the southwestern arid region.

4.2. Time-varying trends in area extent of droughts

The trends in SPEI, precipitation and temperature during Rabi and Kharif seasons at all the grid points over a 50-year sliding window with 10-year time steps between 1901 and 2010 are assessed to understand the changes in areal extent of droughts with the changes in precipitation and temperature over the time. Fig. 8 shows the positive (blue line) and negative (red line) trends for different 50-year windows (1901–1950, 1911–1960, 1921–1970, 1931–1980, 1941–1990, 1951–2000, and 1961–2010).

The figure shows that precipitation has more influence on SPEI compared to temperature during both seasons. The changes in SPEI, precipitation and temperature over a number of grid points during Rabi season (Fig. 8a–c) shows that SPEI decreased (increase in drought severity) during the periods when precipitation decreased. For example, decrease in precipitation at 44 grid points during 1931–1980 caused a decrease in SPEI at 90 grid points. Similar decreases in SPEI during 1941–1990 were observed due to a decrease in precipitation. On the other hand, an inverse relationship between temperature and SPEI is observed. Increase in temperature in recent years (1961–2010) caused an increase in SPEI or more severity in droughts. However, the influence of temperature on SPEI is found less compared to precipitation. The figure shows that precipitation has not changed in any grid points in recent years. However, the SPEI has decreased at a number of grid points which is due to the increases in temperature in most part of the country in the recent years.

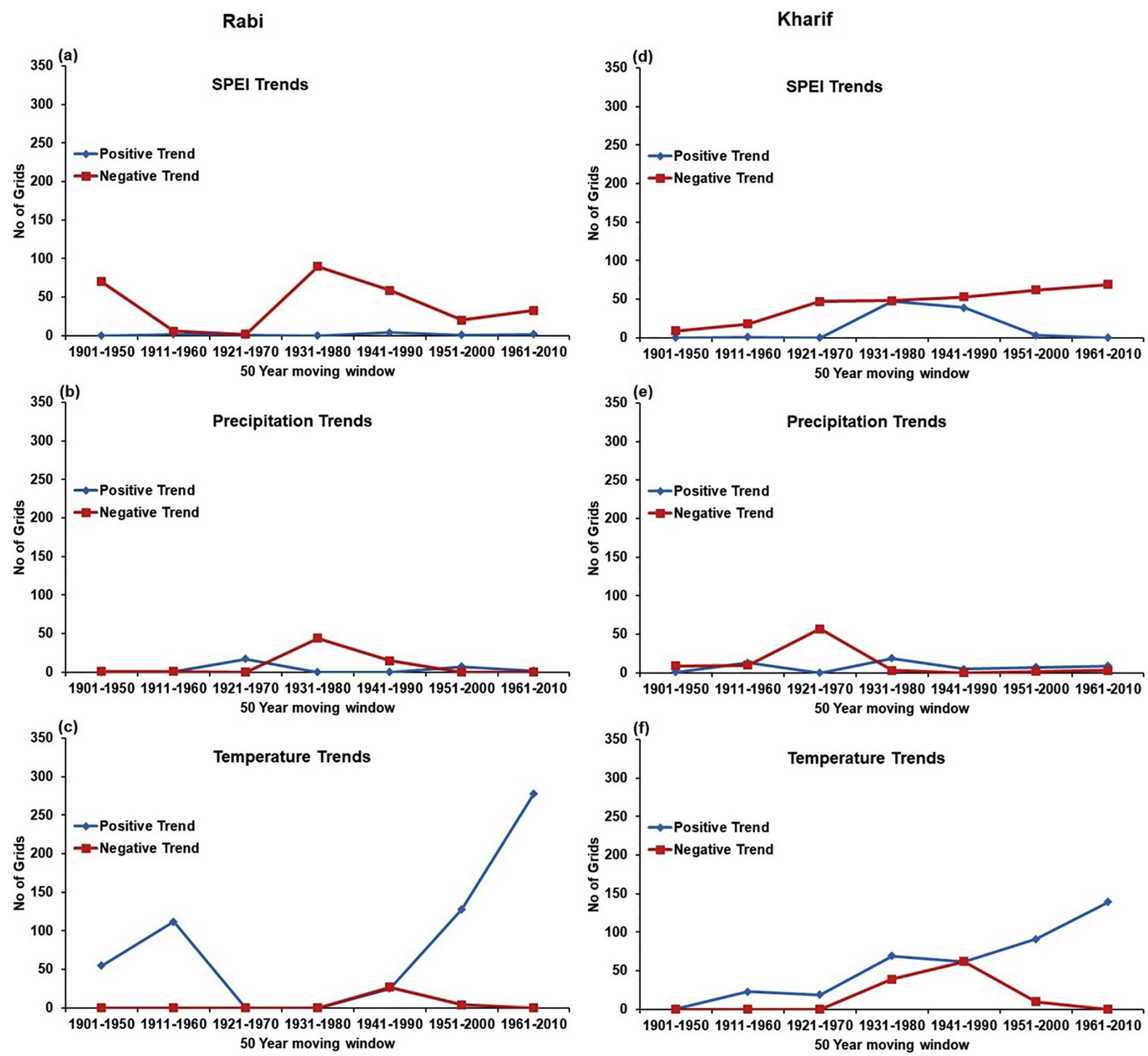

Fig. 8. Time-varying trends in the number of grid points showing significant changes in SPEI, precipitation and temperature during Rabi and Kharif seasons.

A similar result is also found for the Kharif season (Fig. 8d–f). Decreases in precipitation at 57 grid points during 1921–1970 caused a decrease in SPEI at a large number of grid points (47), while an increase in precipitation at a small number of grid points (19) during 1931–1980 caused an increase in SPEI (decrease in drought severity) at a large number of grid points (47). No changes in precipitation in the later period (1941–2010) at any grid point, but continuous increase in temperature at a number of grid points caused a gradual increase in the number of grid points showing significant decrease in SPEI. The results clearly indicate that the recent increase in drought affected area is due to the increase in temperature.

The results indicate that the climate change impact on droughts in a particular season mainly depends on the changes in precipitation. Temperatures in both seasons have increased in almost over the whole country. It is supposed to increase continuously due to global warming. On the other hand, precipitation is not found to change at any of the grid points during both seasons after 1951. Though precipitation has a much higher influence on SPEI over Pakistan, no change in precipitation and increase in temperature has caused an increase in drought severity and affected area in both seasons. As the continuous rise of temperature is very certain, it can be remarked that drought severity would increase in Pakistan due to global warming.

4.3. *Changes in return period of seasonal droughts*

The return period of moderate, severe and extreme droughts during Rabi and Kharif seasons for different 50-year periods over the years 1901 to 2010 are analyzed to verify the results obtained in the previous section. The changes in return periods of Rabi and Kharif droughts are shown in Fig. 9. The return periods estimated at different grid points are presented using box plot. The lower and upper lines of the boxes give the 25th and 75th quartiles of drought return periods, whereas the middle line of the box gives the median value drought return periods at different grid points over Pakistan. The return periods for moderate, severe and extreme Rabi drought (Fig. 9a) are found in the range of 6–7, 12–14 and 20–30 years respectively. Overall, a decreasing trend is

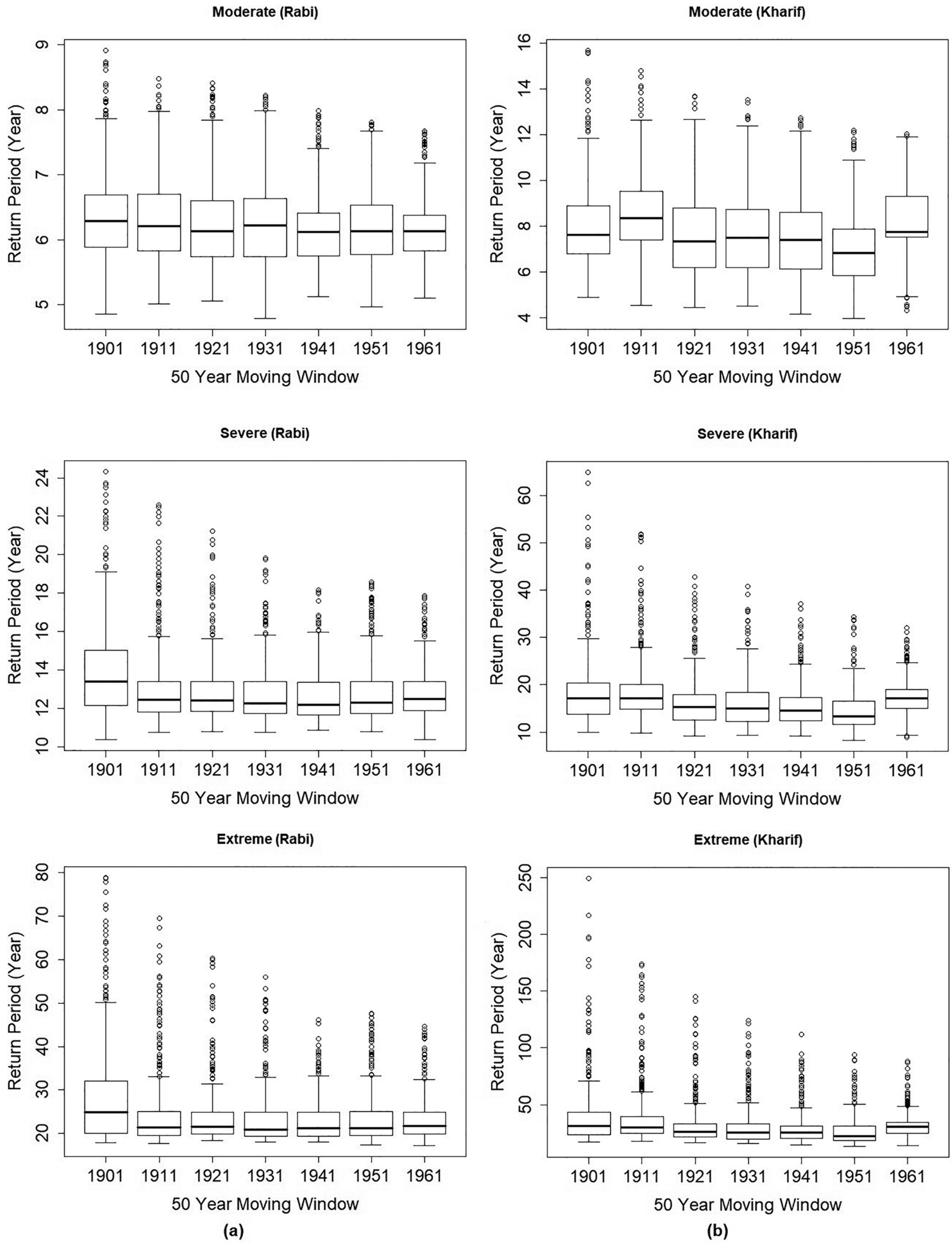

Fig. 9. Return periods of different categories of droughts during (a) Rabi; and (b) Kharif seasons.

observed from the median values of drought return periods, which indicate a gradual decrease in SPEI in recent years. The box plots are found to narrow down gradually over the time. This is mainly due to shortening of upper whisker of the box plot. The decreases of upper whisker of box plots for all categories of Rabi droughts indicate decreases in drought return period or increases in drought frequency in the areas where previously droughts were less frequent. This indicates that rises in temperature all over the country has increased the physical vulnerability of droughts in the regions, which were historically less prone to droughts.

The return periods of moderate, severe and extreme Kharif droughts in Pakistan are found in the range of 7–9, 13–19, and 30–45 years

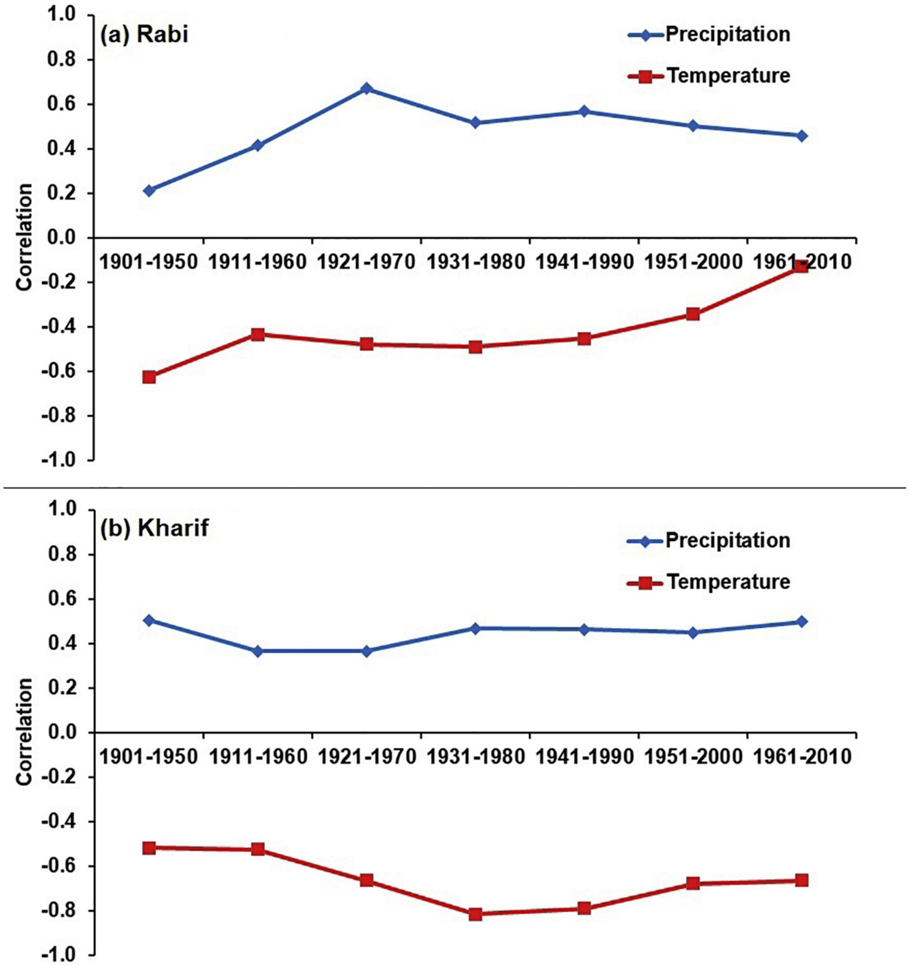

Fig. 10. Relationship of SPEI with precipitation and temperature during (a) Rabi; and (b) Kharif seasons.

respectively (Fig. 9b). A fluctuation in the median value of moderate drought return periods is observed which indicates the frequency of moderate drought is highly variable in Pakistan. However, return periods of severe and extreme Kharif droughts are found to decrease gradually with time. Similar to Rabi droughts, upper whisker of Kharif drought return period for all the categories are found to decrease gradually. Therefore, it can be remarked that increases in Kharif drought return period in the areas where it was previously less frequent. Overall, the results justify the finding that increases in temperature in most part of the country have caused decreases in SPEI and therefore, increases in the frequency of droughts.

4.4. Changes in relationship of SPEI with precipitation and temperature

The changes in association of SPEI with precipitation and temperature are assessed considering a 50-year moving window with a 10-year time step. The obtained results for Rabi and Kharif seasons are presented in Fig. 10. The figure shows that the drought has a positive relationship with precipitation indicating that drought increases when the precipitation decreases. On the other hand, a negative relationship is noticed for drought with temperature. The figures show that the relationship between precipitation and SPEI is more stable with time, while the relationship between temperature and SPEI is highly variable with time. The relationship between temperature and SPEI during Rabi season is found very weak in recent years, while it is found strong during the Kharif season. The results justify the findings that precipitation has more influence on SPEI compared to temperature. The results also suggest that rising temperature would have more impacts on Kharif droughts compared to Rabi droughts. This is justifiable as the Rabi season coincides with winter and therefore, increase in temperature would not affect evapotranspiration much compared to Kharif season, which coincides with summer.

5. Discussions

Droughts are known to be more destructive when they occur during a cropping season (Mishra and Cherkauer, 2010). The effects of droughts during the crop-growing season can be long lasting in a country like Pakistan where the majority of population depend on agriculture for their livelihood (Ashraf and Routray, 2015). The present study revealed that overall precipitation has more influence on droughts compared to temperature in Pakistan. However, arid region in the western part of Pakistan where precipitation is very less, temperature plays a major role in defining droughts. On the other hand, the impact of temperature is less in the northern region where precipitation in high.

Changes in precipitation due to large-scale atmospheric phenomena like monsoon and western disturbances as a result of global warming can have severe impacts on seasonal droughts in Pakistan. Ahmed et al. (2017b) and Hanif et al. (2013) reported that the precipitation in monsoon season has significantly increased over a few places in the north, while Ahmed et al. (2017b), Hanif et al. (2013) and Salma et al. (2012) reported a decrease in monsoon over the west and some southern parts of the country which are historically more prone to droughts. The MMK trend analysis conducted in the present study revealed increased in precipitation in NEM dominated high precipitation

region and almost no significant change in SEM dominated southern and western regions. Increases in precipitation in the NEM dominated region caused increases in SPEI (decrease in drought severity). On the other hand, no change in precipitation, but a large increase in temperature has caused decreases in SPEI (increase in drought severity) in the SEM dominated summer precipitation region.

Ahmed et al. (2017b), Farooqi et al. (2005) and Ringler and Anwar (2013) reported an increase in winter precipitation over a major portion of the country while a decrease in some parts in coastal regions located in the south. However, the MMK trend test in the present study over 1901–2010 revealed almost no change in winter precipitation (Rabi Season) in Pakistan except increases and decreases at few grid points in the north and the west. However, a faster increase in winter daily mean temperature is observed compared to summer daily mean temperature. The increase is found more in the western and the southern parts of the country. A large increase in temperature and no change in precipitation have caused an increase in Rabi droughts over the whole western and southern regions.

Though droughts generally refer to the lack of precipitation over a certain period of time in an area, the present study revealed that increasing temperature is one of the major climate change drivers that would affect the occurrence of droughts in any climatic regions or seasons (Mohsenipour et al., 2018; Murphy and Timbal, 2008; Shiru et al., 2018). The present study revealed that rising temperature due to global warming may bring more droughts with devastating impacts in Pakistan. The increasing severity of droughts estimated in the present study is consistent with the findings of other studies conducted in nearby countries.

Mallya et al. (2016) studied the trends and variability of droughts during 1901–2004 over the Indian monsoon region and found an increasing trend in drought severity and frequency during the recent decades (1972–2004). They also reported droughts are becoming more regional and are showing a general shift to the agriculturally important areas. Das et al. (2016) assessed the trend and behavior of droughts over India during 1901–2008 and reported increases in drought over the eastern part of India was attributed due to decrease in precipitation, whereas the decrease in drought occurrence over the western arid region was mainly because of decrease in PET. They also reported increasing drought condition with extended duration and higher intensity over all regions except northwest of India, where they found reduces in drought duration and lower intensity. Fahim et al. (2016) assessed the droughts in the Khyber Pakhtunkhwa province of Pakistan and showed the increasing temperature as one of the contributing factors of droughts in recent years.

Bazrafshan (2017) assessed the effect of temperature on the historical trend of long-term droughts in different climates of Iran during 1951–2014 and found Iran has experienced severe droughts in recent decades due to decreasing annual precipitation along with increasing potential evapotranspiration. They also reported changing behavior of extreme droughts in arid climates due to variation in temperature. Moradi et al. (2011) investigated the meteorological drought characteristics in Fars province of Iran and noted short term droughts have intensified in recent decades. Tabari et al. (2012) analyzed droughts in the eastern arid and semiarid regions of Iran and found that the eastern regions of Iran have become more arid during 1966 to 2005. Abbaspour et al. (2009) reported a decrease in precipitation is causing an increase in the frequency and intensity of droughts in the dry regions of Iran. They also showed that the southern and eastern regions of the country would experience lesser precipitations and therefore, more susceptible to severe droughts. Amini et al. (2016) studied droughts over the Euphrates-Tigris basin covering some parts of Iran and found most severe and frequent droughts in the past 15 years. Aich et al. (2017) modeled the past and future climate of Afghanistan and reported an increase in drought frequency and magnitude.

Ayantobo et al. (2017) assessed the drought characteristics over mainland China during 1961–2013 and reported more frequent drought over some regions are due to increasing temperature and potential evapotranspiration. Yang et al. (2013) reported increases in drought-affected areas in China over the past 50 years due to spatiotemporal variation in precipitation and temperature. Li et al. (2015) reported drying trend in Southwest China and increased frequency of moderate and severe droughts after 2005. Guo et al. (2018) characterized the droughts in central Asia during 1966–2015 and found most severe drought events occurred during the last half-century. It has been reported that there is a significant increase in temperature and a small decrease in precipitation over Central Asia during recent decades (Hu et al., 2017; Lioubimtseva and Henebry, 2009). The present study revealed that Pakistan is following the similar trend in droughts like the nearby regions.

6. Conclusions

A comprehensive study has been carried out to assess the changes in the characteristics of Rabi and Kharif droughts in Pakistan over the period 1901–2010. The spatial assessment of drought affected area showed that the droughts are mostly concentrated in the southern part of the country in both seasons. A significant increasing trend in drought severity in the SEM dominated southern part for both seasons while a decreasing trend in NEM dominated northern region during Kharif season is observed. Almost no change in precipitation in Rabi season, but a significant increase in NEM dominated high summer precipitation region during Kharif season is observed. On the other hand, a large increase in mean temperature over the whole country during Rabi season and southwestern region during Kharif season is observed. Higher increase in Rabi temperature compared to Kharif temperature is also noticed. The increases in temperature have caused decreases in the return period of severe and extreme droughts during both seasons in a major part of the country. The study revealed that though precipitation has a higher impact on the occurrence of droughts compared to temperature, recent increases in drought severity in Pakistan are due to increases in temperature. Pakistan is experiencing a significant increase in temperature, but almost no change in precipitation, which has made temperature as the dominating factor for defining droughts in recent years. As the continuous increase in temperature due to global warming is very certain, it can be remarked that droughts will be more severe in the country in the near future.

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